Response of Heating Rod in Water Pool in Various Boiling Regimes up to CHF

R. K. Singh[1], A. Rama Rao

Reactor Engineering Division, Bhabha Atomic Research Centre

Mumbai-400085, India

[1]rajks@barc.gov.in

Abstract

Critical heat flux is paramount from consideration of reactor core thermal hydraulics and ensuring fuel pin cladding integrity. Conventionally, CHF measurements are carried out in out of pile test setups using locally placed thermocouples and also by indirect measurement of change in electrical resistance. These measurements have limitations which are well documented in literature. The present knowledge base of acoustic/vibration response in the core due to CHF is also considered as alternate methodology to detect the onset of departure from nucleate boiling (DNB). Study of vibration response in various boiling regimes becomes paramount for such methodologies. Pool boiling experiments were performed to create condition for critical heat flux occurring in the pool and to study fluid structure interactions during different phases of boiling.

Keywords

Critical Heat Flux; Fluid Structure Interaction; CHF Prediction; Response of Bubble Detachment; Vibration of Heating Rod

Introduction

CHF decides how much power can be drawn without burning of heating element in the pool, which can be treated as equivalent to fuel rod in nuclear reactors. Lots of studies have been reported in literature on CHF. Response of the heating element due to fluid structure interaction in the pool is studied in a specially erected setup. Heating elements responds differently at different stages of boiling.

The experiment uses one glass container as water pool. A stainless steel tube is used as heating rod in which current is passed. Current is increased in small steps. At each step the current is held constant for some time for the phenomena to thermally stabilize. As current is increased, power dissipated in rod increases resulting in boiling. The heater tube is held horizontally inside the pool. The heater rod is fitted with a vertical rigid Teflon rod projecting out of pool. A piezoelectric type accelerator is stud-mounted on top of the Teflon rod to pick up the response of the rod during the experiment. Thermocouples were mounted on heating rod to monitor the temperature of heating rod for various power steps. Temperature of bulk fluid at various locations is also monitored. Temperature history of heating rod as well as bulk fluid was recorded with time. The temperature data is important in characterizing heat transfer value from experiment and to see how heat transfer changes in various boiling regimes. Critical heat flux was evaluated by measuring maximum current flow before burning-off of heated rod starts.

Vibration of heating rod was monitored continuously. Initially at low power, single phase heat transfer takes place, then as power increases sub-cooled boiling starts, and then nucleate boiling until occurrence of critical heat flux. As vapor bubble detaches from heating rod, it gives a reaction force to the rod which leads to vibration of heated tube. Since density and frequency of bubbling changes as power changed, heat transfer mode is shifted from sub-cooled boiling to nucleate boiling until critical heat flux occurs. Different bubbling behavior leads to different fluid structure interactions. At the start, vibration is low but as nucleate boiling takes place, vibration increases due to large number of bubble formation, detachment and agitation caused by bubbles in surrounding fluid.

This paper presents a vibration study of heating rod behavior, starting from sub-cooled boiling till critical heat flux in a water pool.

General Arrangement of the Setup

Figure 1 shows the schematic of the experimental set-up for CHF testing with short length single pin CHF in pool boiling condition. Heater pin in figure 1 is a directly heated pin having double ended electrical connection. Other components of the set-up are test pin, D/C power supply unit, accelerometer and data

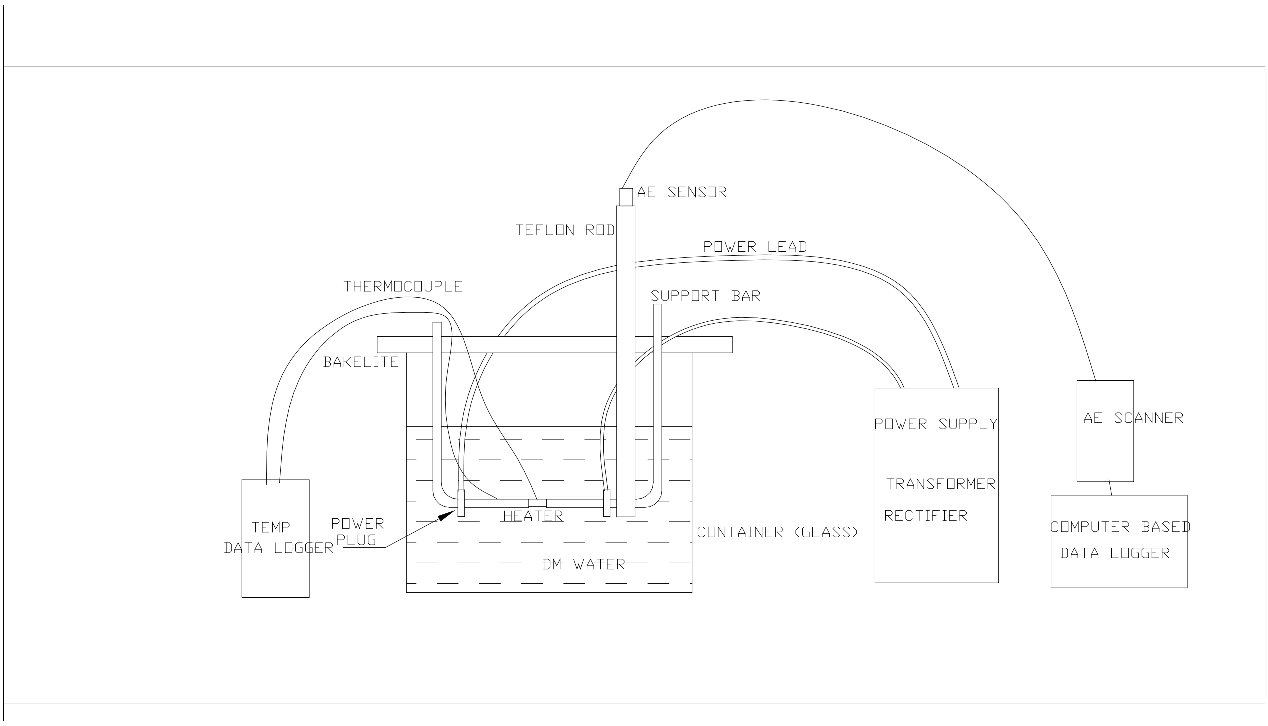

FIG. 1: SCHEMATIC ARRANGEMENT OF THE TEST SET UP

acquisition system, temperature data logger, thermocouples, water container, Voltmeter and ammeter, test stand and bus bar and power supply cables.

Figure 2 shows the photograph of the test set up. The Bakelite strip holds the test pin. The pin is immersed in DM water inside the container which is open to atmosphere.

Power supply cables from the D/C power supply source are connected to the pin either through bus bar or directly. Depending on the resistance of the heating element of the heater pin, heat generation in the pin increases due to passage of current. The pins have provision for thermocouple placement to measure pin surface temperature.

The thermocouples are connected to temperature data logger for recording. The temperature data logger has provision for relay output whose cab gives suitable alarm and trip signal

whenever some measured parameter, viz. pin temperature, value exceeds some predetermined set point. Based on trip signal, power supply to the heater pin will be cut off.

Vibration data logger collects data from accelerometer, which is connected with the test pin via Teflon rod, and records the vibration response (fluid-structure interaction) of the test pin as heating process passes through different thermal hydraulic regimes until occurrence of CHF.

Test Pin

The test pin under consideration is a directly electrically heated. Pin is made of SS- 304 tube (OD- 6 mm, ID- 4.8 mm, heated length- 100 mm). Heater pin is having the double end electrical power input/output facility and the pin is oriented horizontally. 0.5 mm or 1 mm sheath three thermocouples are brazed on the outer surface of the pin by brazing. Thickness is reduced at the central portion of the heater pin to increase electrical resistance hence increasing heat generation rate locally and one thermocouple is located on thinner section. Electrical current passes through the outer sheath generating heat by Joule heating. Both ends of the heater pin are closed by brazed joint with copper rod which are bent to form support structure and can also be used as electrical terminal. Teflon rod is push fitted at one end of the cold part of the heater pin.

Preliminary Description of Instruments Used

Major instruments used are listed below,

D/C Power Supply Unit

DC power supply unit consists of transformer and rectifier. Provision for coarse and fine power manoeuvring is available.

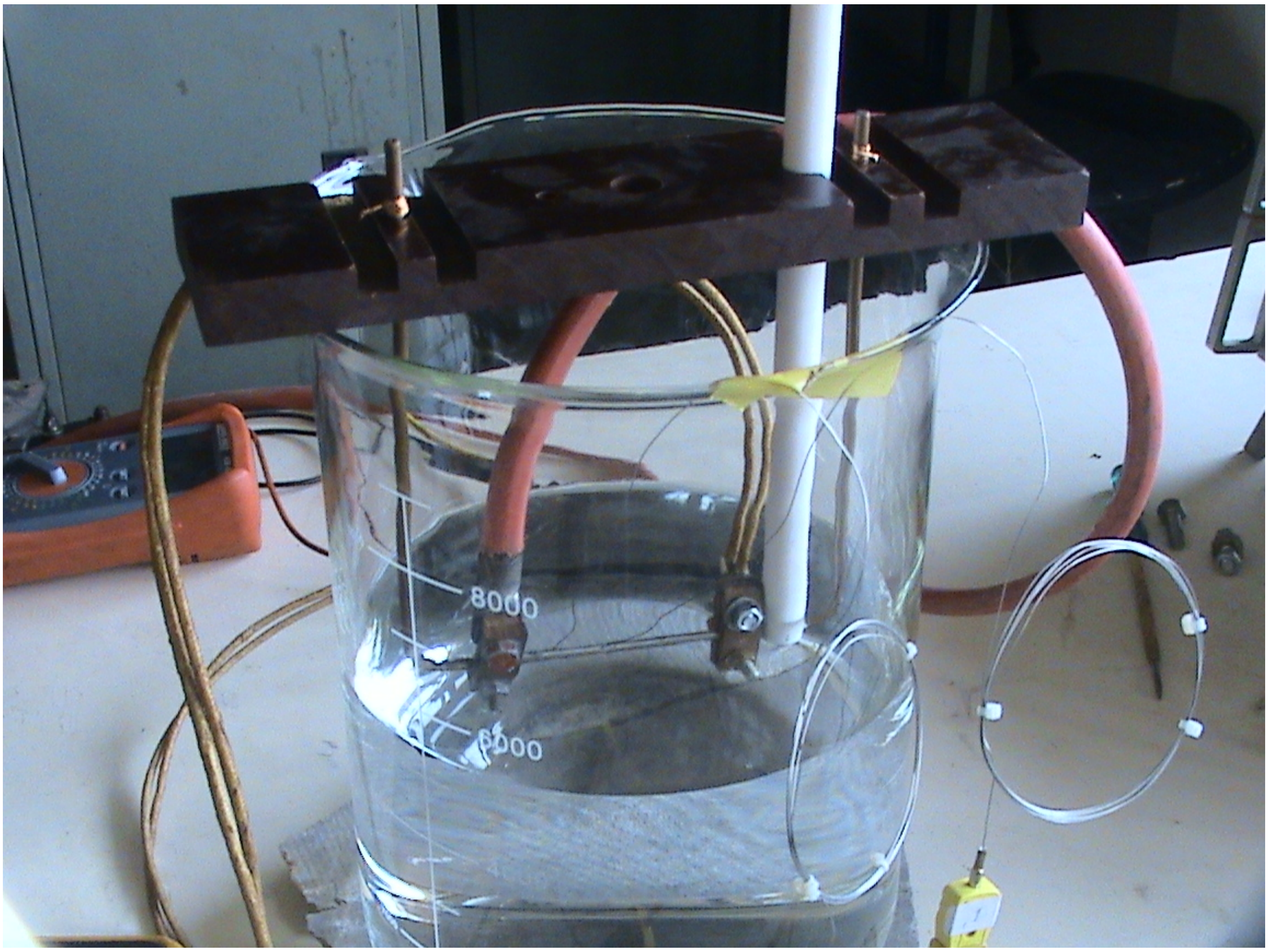

FIG. 2: PHOTOGRAPHS OF THE TEST SET UP SHOWING THE TEST PIN SUBMERGED IN DM WATER

Temperature Data Logger

A multi channel data logger is used for temperature measurement at this facility. The data logger takes input from K-type thermocouple and displays and records the temperature. The data logger can generate multi channel relay output that is to be used for generation of suitable alarm and trip signal. The datalogger is having suitable software for continuous monitoring of recorded data.

Thermocouples

K-type, 0.5 mm or 1 mm sheath OD, ungrounded thermocouples are used for this facility. Length required for the thermocouple is 1 m with 2 m extension cable. Three thermocouples are brazed on the outer surface of the test pin. Output from the thermocouples is fed to the temperature data logger.

Accelerometer and Data Logger

General purpose accelerometers were chosen for this particular set up in view of indirect measurement of acoustic signal emanating, during release of bubbles from the surface of the heating element. The response of long Teflon rod was measured with general purpose accelerometer as only low frequency signals will be transmitted with measureable amplitude. If the measurement were possible directly on the heating rod, acoustic or high frequency accelerometer would have been more suitable and more sensitive to the phenomena of bubble detachment.

Test Procedure

All the instruments used for the experiment are calibrated to ensure the dependable data with high signal to noise ratio. Electrical insulation of the test stand and DM water container was checked then power supply to the test pin was put on. Initially power was increased in steps at some predetermined rate (~5- 10% of the estimated power at CHF). Pin temperature was allowed to stabilize at every step. All the signals were recorded. This process was continued till the test pin power input reached 80% of estimated

pin power at CHF. Then the power was further increased by smaller step size (typically ~ 1-2 % of power at CHF). A sudden jump in rate of pin temperature increase vs. power indicates the occurrence of CHF.

Acceleration response of the heater pin is recorded during the entire spectrum of heat transfer regime from natural convection regime to nucleate boiling and subsequently bulk boiling regime.

Results and Discussion

Vibration signals were recorded up to 2500 Hz with a frequency resolution of 0.5 Hz. The time history of vibration signal clearly showed change for almost every change in current. Every change was followed by 5 to 8 minutes of stabilizing time so that sufficient length of vibration signal was obtained for accurate signal analysis. The entire spectrum of the signal obtained for every 5 to 8 minutes length of signal was examined to locate and trend the changes. Prominent changes were seen in the band of 250 to 350 Hz. From almost noise in this band to slow emergence of signal slowly turning out to be dominating on the 2500 Hz band was identified. The test was repeated with different length of heater element but same Teflon rod. The observation made in band of 250 to 350 Hz was repeating. Figure 3 shows the overall vibration in this band plotted against time of measurement. Time axis was chosen to bring out the effect of bubbles and its dynamics on the heater tube in sub-cooled boiling to nucleate boiling up to occurrence of CHF. Initial gradual increase in the vibration response and then step rise indicates shift from sub-cooled boiling regime to nucleate boiling. High magnitude of vibration was measured when bubble were formed and detached from the heater rod rigorously. The whole setup was found to be shaking with visible vibration.

Figure 4 shows the photograph of heater rod in nucleate boiling regime. The intensity of bubble formation and matching intensity of bubble detachment from the heater rod gives vivid picture of the involved dynamics.

As the current is continuously increased in small steps, vapor production rate also increases continuously; this increases the vibration of heating rod. Up to nucleate boiling regime water keeps on coming back to cool the heated rod. As heat flux is increased more, vapor blanket is formed above the rod and vapor blanket stops water from reaching the rod. When water is not able to reach at some local point in the rod, heat transfer is severely affected and temperature increased rapidly; which causes CHF to occur. It can be seen in figure 3 near CHF point that sudden increase in vibration of heater rod can be utilized as forerunner of

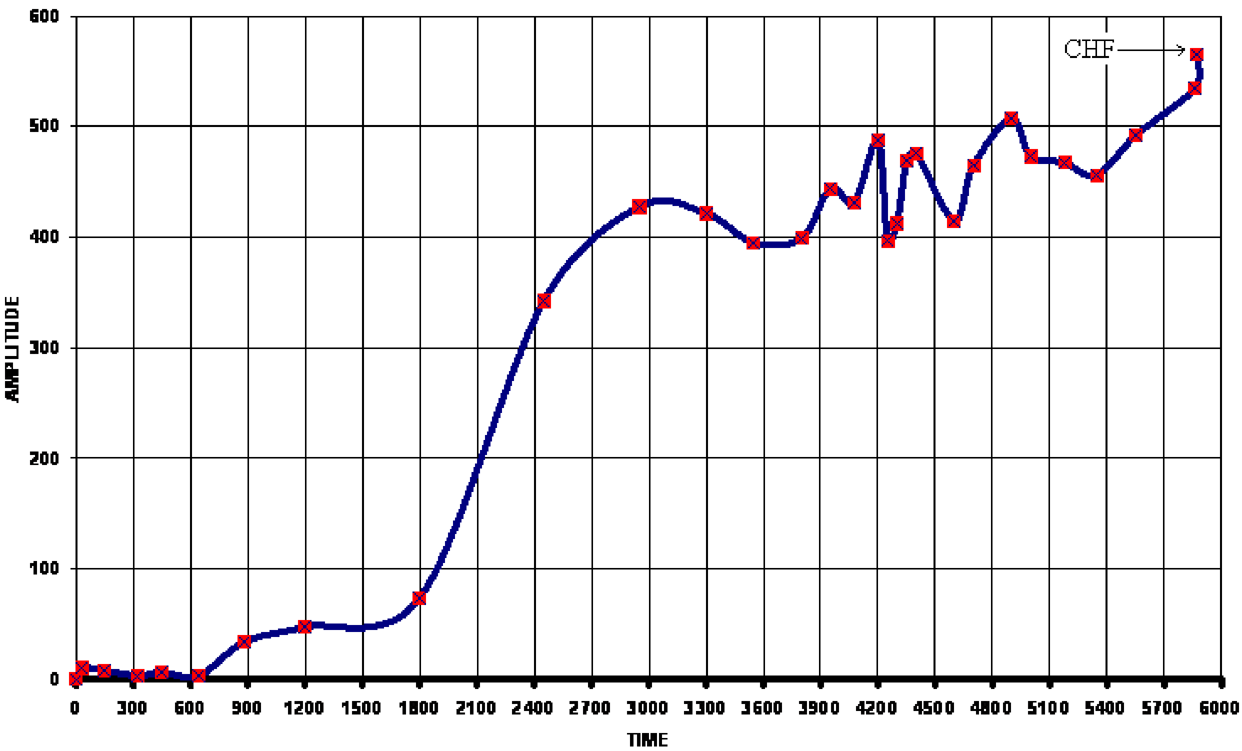

FIG. 3 PLOT OF 250- 350 HZ OVERALL RESPONSE

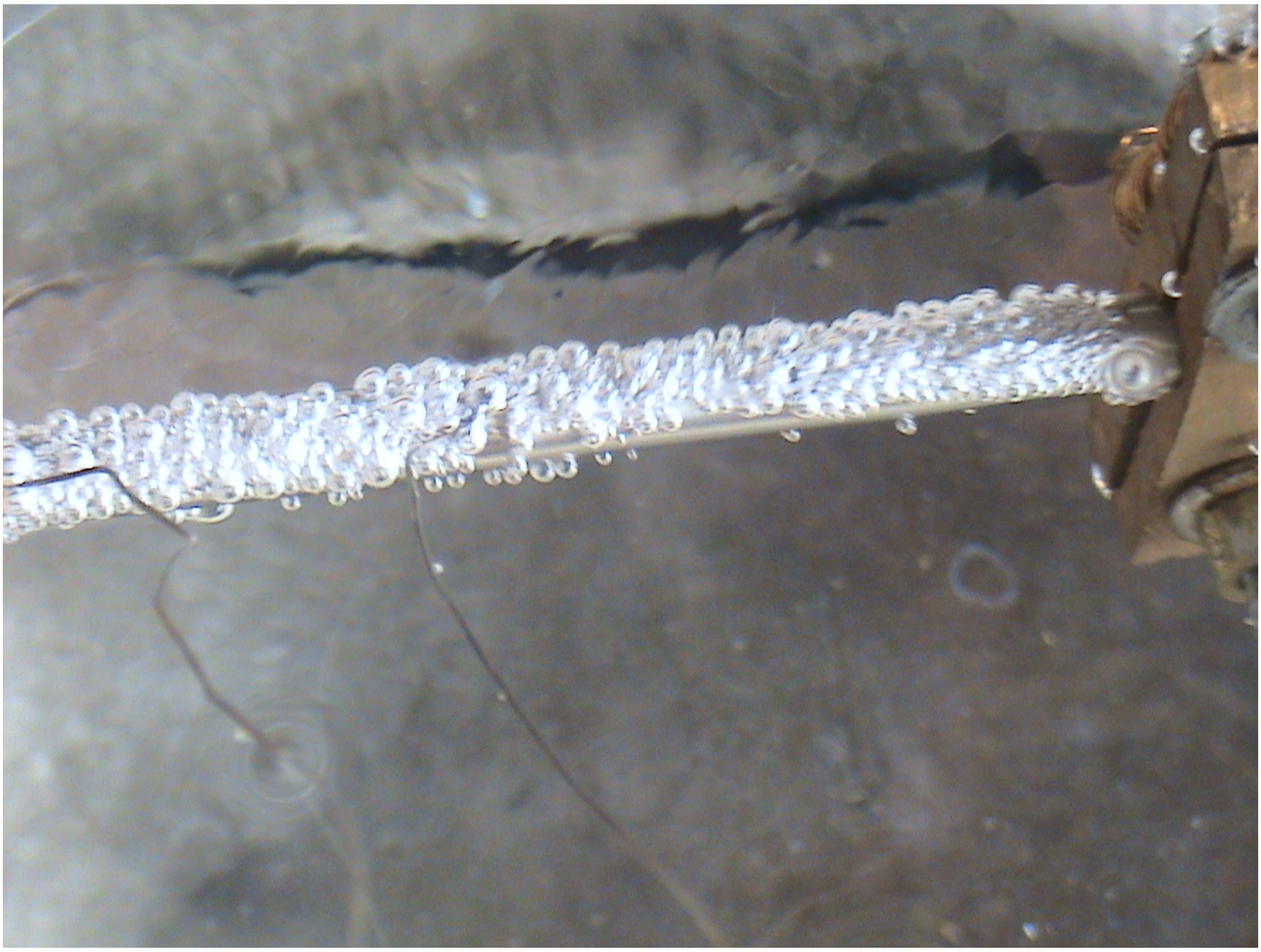

FIGURE 4: TYPICAL PHOTOGRAPH OF NUCLEATE BOILING REGIME

CHF. In figure 4 peak vibrations are measured at occurrence of CHF.

Conclusion

Pool boiling experiments were performed to study the heating rod response during various regime of pool boiling. The measured vibration data shows that vibration response of heating rod changes with various boiling regime. The fluid structure interaction experiment was able to bring out the underlying phenomena. It was found that vibration data reflected the changes in boiling pattern and peak vibrations were measured at occurrence of CHF.

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